In-Vitro investigation of flow profiles in arteries using the Photoplethysmograph

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***Abstract*— The flow profile in the artery reflects the health status of the vessel and generally the arterial system. The aim of this pilot study was to investigate *in-vitro* the effect of flow profiles on reflective photoplethysmography (PPG) signals at different steady state flow rates and levels of vessel constrictions. A simplified model of an arterial system was built, consisting of a steady state flow gear pump, PVC vinyl tubing, reservoir and a clamp with a micrometer gauge. The blood mimicking fluid (2.5% India ink and water solution) was pumped through the model. It was found that the waveforms of the PPG signals fluctuate irregularly and the magnitude of the frequency components was increased below 60 Hz in cases of turbulent flow (*Re* = 2503). These preliminary results suggest that PPG could be the basis for new technologies for assessing the profile of the blood flow in the artery. Future studies have to be carried out with pulsatile flow and more complex models that are more similar to the human arterial system.**

***Clinical Relevance*— The PPG signal reflects changes in the flow profile caused by the stenotic rigid vessel.**

I. INTRODUCTION

Turbulent blood flow can be connected to progression of various cardiovascular diseases and has been shown to damage the red blood cells and endothelial cells of the artery wall [1, 2] resulting in the initiation, progression and development of atherosclerosis [3]. Atherosclerosis causes the thickening of the walls of large and medium arteries. In atherosclerosis a streak of fat develops on the inner wall of the artery, which gradually develops into a thicker fibrous plaque and results in stenosis and turbulent blood flow. Doppler ultrasound is often used for the detection of stenosis by measuring the blood flow velocity in the carotid and lower extremity arteries [4, 5]. However, this method is relatively expensive, intermittent, and needs a trained operator. Therefore, a simple, low cost and operator undependable detection system of turbulent blood flow in arteries may offer an early screening of arterial disease.

Over the past decade various optical systems based on the technique of photoplethysmography (PPG) have been widely investigated for various applications, including the monitoring of the cardiovascular system [6, 7]. Often PPG signals are related to the blood volume change of the microvascular bed of tissue and explained through the simplification of the Beer-Lambert law model [8]. The results from *in-vitro* studies with pulsatile flow and rigid tubes show that there are associations between blood flow and the AC components of the PPG signal [9]. In addition, the evidence from *in-vivo* studies also confirmed the findings from the studies on rigid vessels [9, 10]. Despite the promising results, flow rate estimation using PPG method is still a challenge. Furthermore, the previous studies have not investigated flow profile characterization using PPG.

The aim of this study is to characterise the flow dynamics in the rigid vessel, using PPG, in an effort to identify and distinguish the differences between laminar and turbulent flow patterns in the case of stenotic tubes. This experiment aims to explore laminar and turbulent flow separately utilising a custom-made *in-vitro* flow rig. The flow dynamics were assessed using a simplified model of the human arterial system.

II. METHODS

A. *Overview of experiment setup*

The overview of the experiment setup is given in Figure 1. It consists of four main parts: the gear pump, PVC vinyl tubing (artificial blood vessel), reservoir for blood mimicking solution, and a clamp with micrometer gauge to create controlled constrictions to the tube. The PVC clear vinyl tube inner and outer diameters were 4.5 mm and 6.5 mm, respectively. The diameter of the tube is similar to the lower extremity arteries, such as femoral and popliteal. A 2.5 % India ink (Liquid Indian ink, Winsor & Newton, UK) and distilled water solution was used as a blood mimicking fluid. The magnetic stirrer was used under reservoir in order to avoid the deposition of the ink particles. The variable supply voltage of the gear pump (GP-301-24H, Reverso Pumps, USA), controlled the steady state fluid flow rate in the system.

Two reflectance PPG sensors were used in the experiment setup. The tube holder was designed to attach the optical sensors to the tube. The first optical sensor (OS1) was placed before the clamping screw and the second optical sensor (OS2) after. The distance from the output of the gear pump to the OS1 was 50 cm, which minimised any disturbance in flow that originated from the outlet of the pump. The distance from the clamping screw to OS2 was 24 mm. The reflectance mode PPG sensors included a red LED (660 nm) and a photodiode (BPW34, Osram, Germany). The distance between the centre points of the LED and photodetector was 8 mm. Optical components were mounted into black plastic housing to minimise the direct optical coupling between each other. The optical sensors were connected to blood oxygen sensor evaluation modules AFE4490SPO2EVM (Texas Instruments, USA), which enables the recording of PPG signals with a

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sampling rate of 500 Hz using the dedicated software AFE44x0SPO2EVM GUI ver 2.0 (Texas Instruments, USA). The modules also feature the ability to exclude ambient light recording from the procedure.

Pressure drops on the segment of the tube used was measured using a differential pressure sensor (SSCSNBN005PDAA5, Honeywell). The T-connectors were connected to the tube before and after OS1 and OS2, respectively. The locations of the T-connectors are marked on Figure 1 as P_1 and P_2, where the pressure is measured. The T-connector distance before OS1 was 20 cm. The differential pressure sensor was connected to the T-connector with tube, which included a hydrophobic filter. The output voltage of the differential pressure sensor corresponds to the pressure difference P_1-P_2 in the tube.

The Doppler shift signal was monitored using the Acuson Sequoia 256 Cardiac Ultrasound Machine (Siemens, Germany) and the pulsed wave spectral Doppler mode for the calculation of flow velocity in the tube. The 8 MHz Acuson 8L5 linear array ultrasound transducer probe was placed above the tube after the OS2 using a stand with a clamp. Aquasonic clear ultrasound gel (Parker Laboratories Inc., USA) was used to improve the sound conductivity between the tube and the sensor.

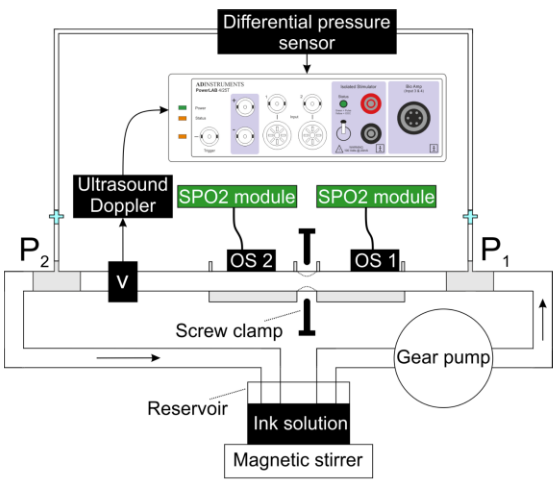

Figure 1. Overview of the experiment setup.

Doppler shift signal was taken from the 6.35 mm TRS socket of the ultrasound machine. The Doppler shift and the pressure sensor signals were recorded with PowerLab 4/20T (ADInstruments, Australia) data acquisition device. The signals were recorded synchronously with a sample rate of 20 kHz using Chart 5 software (ADInstruments, Australia). The sample rate was selected according to the highest possible velocity of the fluid in the tube, which determines the highest frequency component of the Doppler shift signal.

B. *In-vitro experiments without constricted tube*

The aim of the experiments without the constriction in the tube was to characterize the changes in the PPG signal during laminar and turbulent flow profiles. The Reynolds number, *Re*, quantifies when turbulent flow will occur in a particular situation and it can be calculated using the following equation:

$$Re = \frac{\rho \cdot V \cdot D}{\mu}, \tag{1}$$

where ρ is the density of the fluid, V is the flow velocity, D is the diameter of the tube, and μ is the dynamic viscosity of the fluid. Roughly, laminar flow occurs when $Re < 2300$ and turbulent flow occurs when $Re > 2900$. The flow rates for the given Reynolds number are according to the experiment setup parameters 9.10 mL/s and 11.47 mL/s, respectively. Therefore, the flow rate in the tube was varied from 6.6 mL/s to 22.7 mL/s (with variable step size between 0.2 mL/s and 5.8 mL/s) in order to cover both flow patterns. Firstly, the pump voltage was increased to achieve the desired flow rate level. Secondly, the recording of pressure and Doppler shift signals commenced 10 seconds later, followed by the start of the PPG signal recording with both modules. At each flow rate 80 seconds of PPG signals were recorded. The recording length was selected on the basis that intuitively the turbulent flow profile should cause the changes in higher frequencies components of the signal due to the generated vortices.

C. *In-vitro Experiments with constricted tube*

The aim of the experiments with the constricted tube was to simulate the artery with different levels of stenosis and to characterize the changes in the PPG signal. The flow rate in the tube was kept constant at around 7.3 mL/s. The constriction was changed from 0 mm to 3.4 mm (in steps of 0.2 mm) using the clamp. At each level of constriction, the PPG signal, pressure, and Doppler shift signals were recorded as described in the previous section.

D. *Data analysis*

The post-processing of the signals was carried out in MATLAB. All PPG signals were truncated to 80 seconds. The spectrums of the PPG signals were computed using Fast Fourier Transform and smoothed using $1/n$ octave smoothing (n=1).

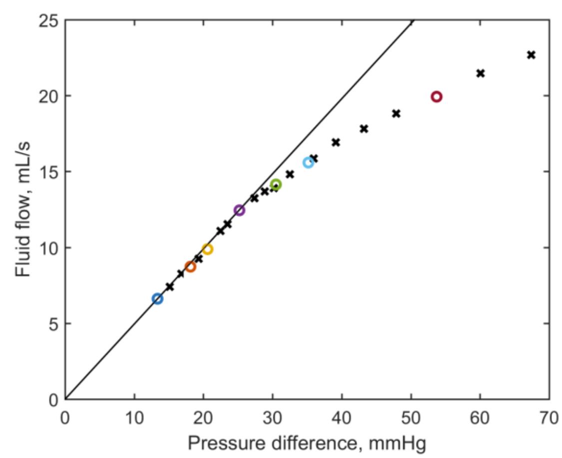

Figure 2. Relationship between pressure difference and flow rate. Black line is the linear relationship between pressure difference and flow rate, which is obtained based on the data point with lowest flow rate (blue dot).

The flow velocity was calculated from the Doppler shift signals using the following algorithm. The average power spectrum was first computed and then the power spectrum was normalised according to its maximal value, lastly the highest frequency was detected, where the normalized power spectrum magnitude crossed the threshold of 0.15. The flow velocity was calculated according to the detected frequency, the speed of sound, and the angle and frequency of the ultrasound probe. The flow velocity algorithm was calibrated prior to the experiments.

III. Results

The flow rate was varied in the experiment without constricting the tube resulting in the pressure differences recorded on the scatter plot in Figure 2. The data points represent the average flow rate and pressure difference of the experiment at each flow rate. The relationship between flow rate and pressure difference should be linear during the laminar flow. Therefore, the black line was constructed on Figure 2 based on the data points with the lowest flow rate and pressure difference (marked with blue circle). It is visible that the data points have deviated from the linear line above the flow rate of 12.4 mL/s, which can be explained by the onset of turbulent flow.

The differences in the PPG signal spectrums and waveforms, which were obtained with OS1 at different flow rates are illustrated in Figure 3a and b, respectively. The colours of the waveforms in Figure 3a corresponds to the flow rates given in the legend of Figure 3b. The frequency spectrum was divided to frequency bands A to D in Figure 3b. It is notable that at the flow rate of 9.9 mL/s and above the PPG signal waveform is randomly fluctuating. In addition, there are notable differences between the spectrums of PPG signals in case of laminar and turbulent flow patterns in the frequency bands of C and D.

Figure 4 shows the PPG signals and the spectrums of the experiments with the constricted tube. Similarly, to the Figure 3b, the frequency spectrum was divided to frequency bands A to D shown in Figure 4b and d. There are notable differences between signal waveforms and spectrums before and after the constriction of the tube. Furthermore, the differences are similar to the experimental results without tube constrictions.

IV. Discussion

A simplified model of the rigid vessel arterial system was built, and experiments were carried out to analyse the steady state flow dynamics caused by changes in the flow rate and stenosis size and assessed with a reflectance PPG signal. It was found that there are notable differences in the PPG signal between laminar and turbulent flow profiles. Furthermore, similar differences in the behaviour of PPG signals were found in the case of the constricted tube.

According to the theoretical calculations and the experimental results (Figure 2) the laminar flow pattern transforms to turbulent between the flow rates of 9.1 mL/s and 12.4 mL/s, respectively. In the case of laminar flow, the fluid and light absorbing ink particles flow in smooth continuous lines that do not mix. Therefore, the relatively stable PPG signal waveforms can be explained during the laminar flow profile (Figure 3a). In addition, the spectrum bands B to D of the PPG signals were all similar below the flow rate of 9.9 mL/s.

The increase in the flow velocity caused an increase in Reynolds number according to Eq. 1 and the flow profile became turbulent. Different sizes of unsteady vortices, which interact with each other, appeared during the turbulent flow and the flow behaviour became irregular and chaotic. Similarly, the irregular behaviour of the PPG signal waveform is visible in Figure 3a at the flow rate of 9.9 mL/s (*Re* = 2503) and above. The magnitude of the frequency components was observed to increase in spectrum bands A to D, which can be explained by the irregular movement of light absorbing ink particles in the fluid. It must be noted that the amplitude of the low frequency fluctuations in the signal and in its' spectrum bands A to B was decreased while the flow rate was increased after the onset of turbulent flow profiles.

The turbulence increased the energy loss due to friction and therefore a larger pressure difference was needed to drive a given flow. Therefore, the relationship between flow rate and pressure becomes non-linear, which is observed in Figure 2. Increasing the flow rate in the tube induces irregular fluctuations, observed by the PPG sensor, and were present before the pressure-flow relationship turns to non-linear.

In stenotic arteries, the critical Reynolds number is lower and the turbulent flow profile onsets at lower flow rates. However, in this study the flow rate was kept constant with a laminar flow profile and instead the level of stenosis was varied to change the flow profile to turbulent. No changes were visible in the PPG signal spectrum and waveform in the upstream of the constriction (Figure 4a and b). However, the fluctuations could be observed in the waveform downstream, starting around 50 % (2.6 mm) of the constricted tube (Figure 4c and d).

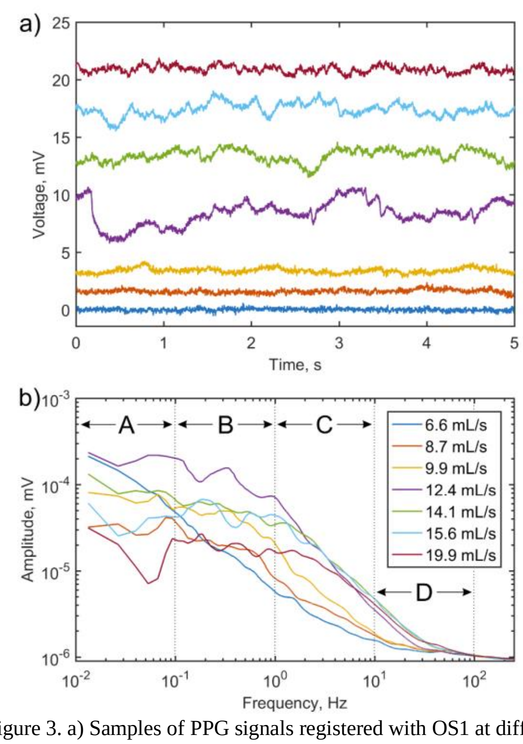

Figure 3. a) Samples of PPG signals registered with OS1 at different flow rates, signals all offset artificially for illustrative purposes. b) PPG signal spectrums at different flow rates.

In our study, the optical sensor (OS2) was placed at a distance of 6 times the diameter of the tube from the constriction. The amplitude of velocity fluctuations were found maximal at the same distance in the simulation studies of flow dynamics in a stenotic tube [11]. As well in this study [11] the simplified model and steady state flow was used.

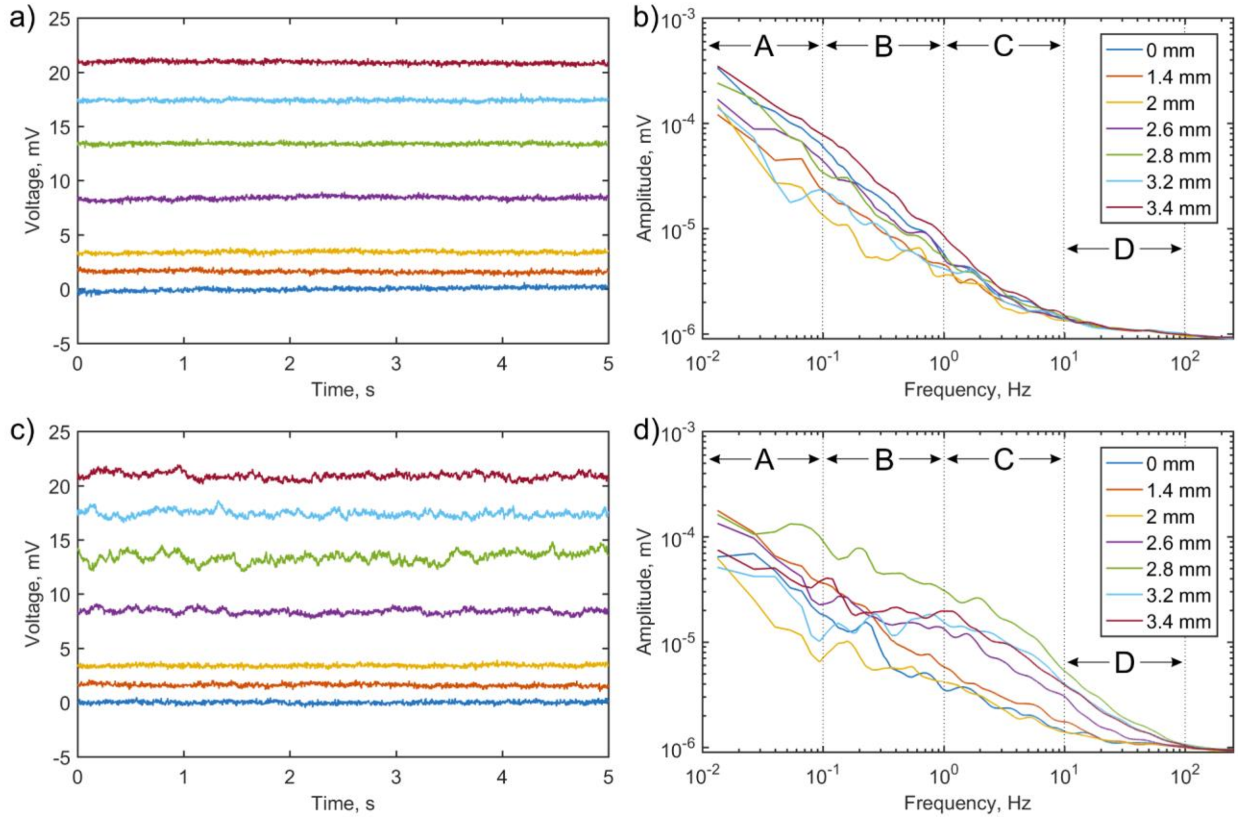

Figure 4. a) Samples of PPG signal waveforms recorded with OS1, and b) spectrums at different levels of constricted tube. c) PPG signal waveforms recorded with OS2 and d) spectrums at different levels of constricted tube. All signals are offset artificially for illustrative purposes.

Therefore, it can be concluded that the effect of the turbulent flow to the PPG signal was maximised in our study. Nevertheless, possibly the amplitude of the fluctuations in the PPG signal might be dependent on the distance from the constriction [11] and should be observed in future studies. In addition, the flow dynamics should be investigated using PPG sensors in a system that provides a pulsatile flow and a model that is more similar to the physiology of the human arterial system.

V. Conclusion

The effect of the flow profile on the PPG signal at different steady state flow rates and levels of tube constriction were investigated using a simplified model of the human arterial system. As a result, the differences in the PPG signal waveforms and spectrums were observed. The findings of this preliminary study provide some confidence that the PPG signal monitoring techniques, such as PPG, could be the basis for the technology that may be used to detect the blood flow profile in the artery. Future studies have to be carried out with pulsatile flow characteristics and more complex *in-vitro* models similar to the human arterial system.

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